

Deprojection technique for galaxy cluster considering point spread function

WANG Yu-Sa Jia Shu-Mei Chen Yong

(Key Laboratory for Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China)

Abstract We present a new method for the analysis of Abell 1835 observed by XMM-Newton. The method is a combination of the Direct Demodulation technique and deprojection. We eliminate the effects of the point spread function (PSF) with the Direct Demodulation technique. We then use a traditional deprojection technique to study the properties of Abell 1835. Compared to that of deprojection method only, the central electron density derived from this method increases by 30 percent, while the temperature profile is similar.

Key words PSFdirect demodulationdeprojection, Abell 1835, galaxy cluster, XMM-Newton

1 Introduction

Being the largest and most massive celestial bodies in the universe, galaxy clusters are the ideal laboratories for studying large-scale structure of the Universe as well as dark matter, through which the cosmological model^[1] could be tested. The center of galaxy cluster is extremely complex, and the observation is susceptible to interference. The XMM-Newton observatory is an ideal instrument for observations of galaxy clusters for its excellent spatial and spectral resolution. EPIC pn and MOS are the main instruments onboard XMM-Newton designed for X-ray detection. However the PSF of pn and MOS is not ignorable, which makes the spatial resolution worse and causes the analysis at the central cluster inaccurate. XSPEC could eliminate the effects of PSF through fit-ting several spectra parameters^[2]. However, this method can not be used with deprojection^[3] simultaneously, which is an open problem for many years in the analysis of clusters, and the fit models here do not consider the energy dependence of the PSF.

The direct demodulation (DD) is an effective method for image restoring^[4]. Through Lucy iterations^[5] with constraints of background^[6], the restored image has better spatial resolution, helping us learning of galaxy clusters greatly. The DD combined with deprojection is a new method which can do PSF correction and deprojection simultaneously without empirical model completely. Comparing to the above method, the DD is more effective for the sensitivity

and spatial resolution, even if the statistic and signal-to-noise ratio is bad.

Abell 1835 ($z=0.2523$) has a relaxed structure in which a large cooling flow has been found by ROSAT, ASCA and XMM-Newton^[7, 8, 9, 12]. The luminosity of Abell 1835 is sufficient to DD, and its relaxed and symmetry structure is suitable for deprojection. In this paper we restore pn images in different energy channel of Abell 1835 (observation ID 0098010101); and then we employ a traditional deprojection technique applied in several clusters successfully^[7]. Finally, the spectra with-out PSF and projection effects are obtained. This is the first time to deproject a galaxy cluster considering PSF.

The structure of this paper is as follows: section 2 describes PSF, DD and processes the data of Abell 1835 with DD; section 3 presents the deprojection method, the fit results such as the temperature profile and the electron density, and the error estimation; then we conclude the results in section 4.

2 Direct Demodulation

We can use the Lucy iteration^[5] (eq. 1) with background constraints to restore the sub-images of Abell 1835 in 34 different energy bands.

$$f^{(r+1)}(i) = f^{(r)}(i) \sum_k \frac{P(k, i) d(k)}{\sum_{i'} P(k, i') f^{(r)}(i')} / \sum_k P(k, i) \quad (1)$$

where $f^{(r+1)}(i)$ can be derived from the initial

1) E-mail: wangyusa@mail.ihep.ac.cn

2) E-mail: jiasm@mail.ihep.ac.cn

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values, $f^{(0)}(i)$, with several iterations and background constraint.

The average value of each energy band is taken for the calculation of PSF, which is a function of energy and angle. The steps to process a sub-image are as follows: (a) Select a region of 100x100 with the center (263, 279) as the DD region, about 500500 arcsec square (1 bin = 5arcsec); (b) Find the positions of the gaps between pn CCDs; (c) Select a circle, whose center is the most luminous in the sub-image and the radius is 120 pixels; calculate rest region without CCD gaps as back-ground; (d) Iteration with the above background; (e) Combine 90x90 of DD region with the rest of original sub-image into an intact sub-image, which can avoid the edge error of DD region.

Because the DD processes the iteration with physical limit, its error is hard to obtain through the direct error estimation. The error depends on the PSF, background, shape of source and iteration times. We find that the 10 times iteration is the best choice for DD. Obvious dispersion will appear in the image when the iteration time is more than 10, while the result is insufficiently stable when less than 10. For estimating the errors of DD, we create 20 images with the Poisson distribution by convolving the result f and the PSF of each energy band; DD the 20 images one by one and get 20 different values of f which is $f'_j (j=1, \dots, 20)$. We use the standard deviations of f'_j as the errors of f .

We take the 0.3-0.4keV sub-image as an example. The original and the PSF-corrected images are shown in Fig.1. The counts in each ring are calculated before and after DD. The restored image shows a much higher counts in the central region (Fig.2).

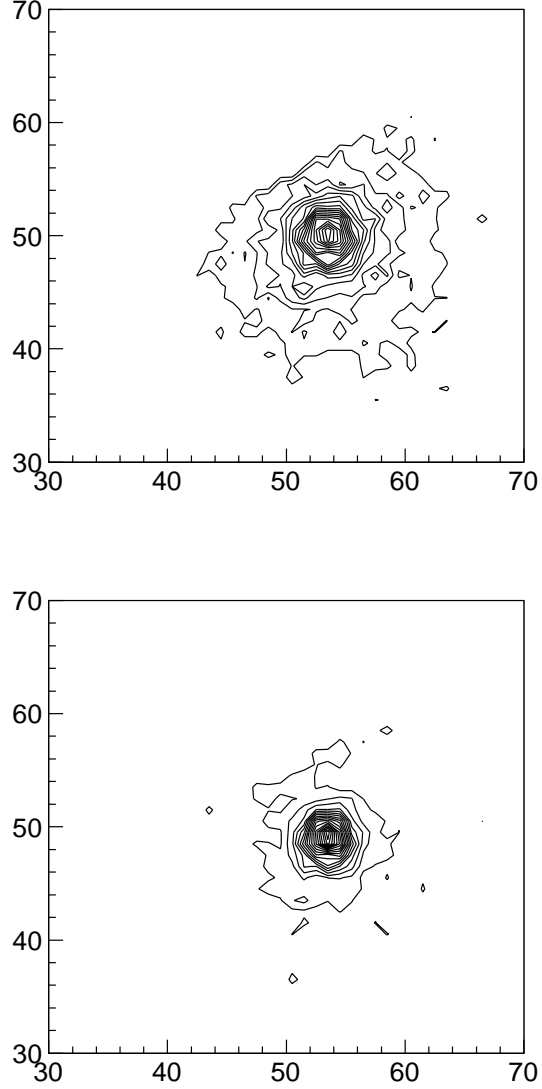


Fig. 1. The top is the original image; the bottom is the image after PSF correction.

Table 1. The fit results of the spectra. T1 and T2 are the temperatures in the double temperature model. A1 and A2 are the abundances in the double temperature model. The error bars are at the 90% confident level..

ring/arcsec	T1/keV	T2/keV	A1	A2	Norm1/($10^{-3}cm^{-5}$)	Norm2/($10^{-3}cm^{-5}$)	$\chi^2_{red}/d.o.f$	Note
0.0-0.25	$1.21^{+0.19}_{-0.18}$	$7.95^{+1.05}_{-0.89}$	$0.21^{+0.17}_{-0.09}$	$0.59^{+0.17}_{-0.19}$	$0.80^{+0.32}_{-0.37}$	$3.14^{+0.24}_{-0.25}$	1.340/28	DD+deprojection
	$1.11^{+0.26}_{-0.17}$	$6.18^{+0.88}_{-0.59}$	$0.11^{+0.07}_{-0.04}$	$0.45^{+0.10}_{-0.10}$	$0.60^{+0.30}_{-0.20}$	$1.95^{+0.14}_{-0.21}$	1.364/28	DD
0.25-0.75	$0.62^{+0.23}_{-0.22}$	$7.89^{+0.98}_{-0.74}$	$0.03^{+0.04}_{-0.02}$	$0.34^{+0.14}_{-0.12}$	$1.21^{+0.38}_{-0.41}$	$4.49^{+0.21}_{-0.24}$	1.473/28	DD+deprojection
	$0.91^{+0.20}_{-0.14}$	$8.14^{+0.65}_{-0.52}$	$0.04^{+0.03}_{-0.02}$	$0.39^{+0.08}_{-0.07}$	$1.32^{+0.30}_{-0.28}$	$5.28^{+0.17}_{-0.24}$	1.630/28	DD
0.75-1.5	$1.37^{+2.09}_{-0.63}$	$14.20^{+15.16}_{-3.12}$	$0.03^{+0.11}_{-0.03}$	$0.37^{+1.35}_{-0.34}$	$1.04^{+1.04}_{-0.44}$	$3.45^{+0.36}_{-1.31}$	1.031/28	DD+deprojection
	$1.09^{+0.85}_{-0.40}$	$12.15^{+4.48}_{-1.79}$	$0.02^{+0.04}_{-0.02}$	$0.31^{+0.31}_{-0.20}$	$0.89^{+0.39}_{-0.29}$	$2.99^{+0.23}_{-0.44}$	0.853/28	DD
		$9.04^{+0.82}_{-0.69}$		$0.25^{+0.15}_{-0.15}$		$4.03^{+0.13}_{-0.13}$	1.631/31	DD+deprojection
		8.27		0.23		3.45	2.167/31	DD
1.5-2.25		$7.20^{+0.94}_{-0.70}$		$0.30^{+0.19}_{-0.18}$		$2.65^{+0.12}_{-0.12}$	1.153/31	DD+deprojection
		$7.91^{+0.84}_{-0.80}$		$0.31^{+0.17}_{-0.16}$		$2.04^{+0.08}_{-0.08}$	1.789/31	DD

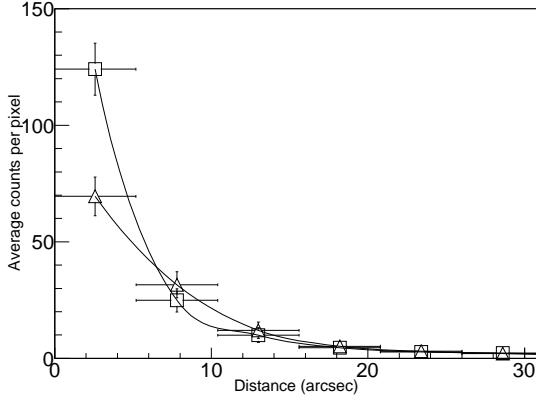


Fig. 2. The average counts in each ring before and after DD. Triangles and squares represent the original counts and the counts after PSF correction, respectively.

3 Deprojection and spectral analysis

3.1 Deprojection

Assuming the structure of Abell 1835 is spherically symmetric and the spectra of each ring for the deprojection are the same, then the deprojected spectra could be calculated through eliminating the contribution from the outer rings for all spectrum components. We divide the sub-image into 8 annular areas, whose center is located in the most luminous pixel, and use the utmost ring ($6' - 8.33'$) to obtain the X-ray background. However, the signal in the seventh ring is almost background, so we only consider the inner sixth rings ($\leq 6'$).

3.2 Spectra analysis

Since different version of SAS and RMF of pn could derive different results, so we use SAS 8.0 and XSPEC 12.4.0 in this paper all the time. We analyze the DD and deprojected spectra of pn data in XSPEC with a single and a double temperature thermal plasma model (eq.2 and 3) as follows:

$$Model_1 = Wabs(n_H) \times Mekal(T, z, A, norm) \quad (2)$$

where $Wabs$ is a photoelectric absorption model^[10] and $Mekal$ is a single temperature plasma emission model^[11].

$$Model_2 = Wabs(n_H) \times (Mekal(T_1, z, A_1, norm_1) + Mekal(T_2, z, A_2, norm_2)) \quad (3)$$

The latter is the double temperature model implying there are two components in the central region with different temperatures.

Because the outer region ($3.33' - 6.0'$) contains pixels out of DD region, we ignore this ring and its adjacent ring ($2.25' - 3.33'$). We fit the three rings ($0' - 1.5'$) of the central region with a double temperature model with free abundance. It was found that the region ($0.75' - 1.5'$) can be also fitted well by a single temperature model like the outer region ($1.5' - 2.25'$).

As shown in Table1, the normalization of the high temperature component in the innermost region is about 60 percent higher than that of deprojection only. It means that the central electron density increases by about 30 percent, implying a much larger gradient of the gas density in the central region of Abell 1835. However the resultant temperature profile is more or less the same as that of the deprojection only, except for the innermost region where the temperature of the high component increases significantly.

Since the profile of PSF is dependent on the photon energy (Fig.3), the temperature of the restored spectra could be different from the original. The PSF of high energy is steeper than that of low energy around the several adjacent bins, especially in the inner 2 bins. In addition, the changes of the normalization of the restored spectra will affect the spectra of its inner rings during the deprojection process.

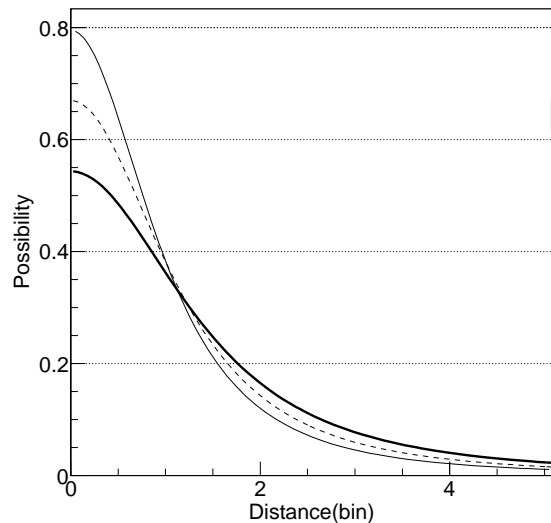


Fig. 3. The PSF of pn. The heavy solid line, the dotted line and the light solid line represent the PSF of pn of 0.3keV, 3.8keV, 7.8keV, respectively (1 bin = 5 arcsec).

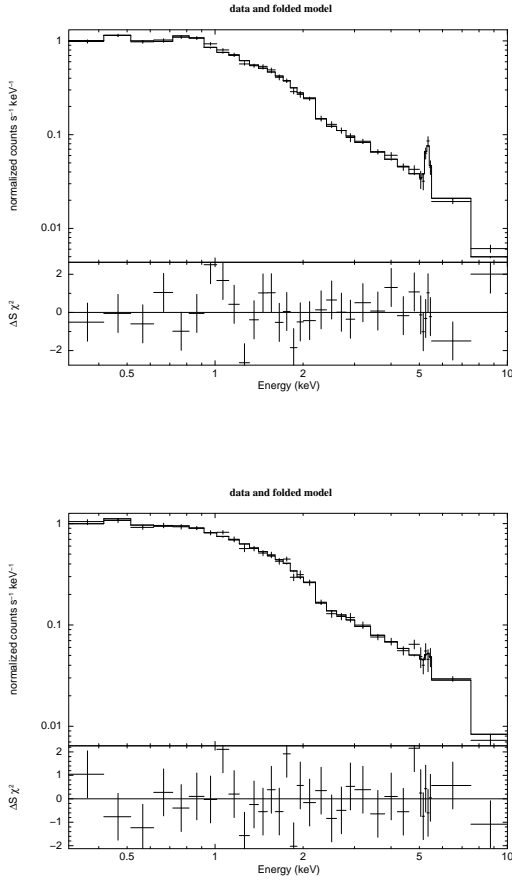


Fig. 4. Spectra fitted by the double temperature model with free abundances. The top is for the ring of $0' - 0.25'$; the bottom is for the ring of $0.25' - 0.75'$.

The spectra of the two innermost rings ($0' - 0.25'$, $0.25' - 0.75'$) fitted by the two temperature models are shown in Fig.4.

4 Conclusion

We have applied a combined DD and deprojection technique to analyze the pn data of Abell 1835 observed by XMM-Newton observatory. The results show that it is reasonable to analyze the cluster data with the combined DD and deprojection technique. Comparing to the analysis by deprojection only, we derive a similar temperature profile but a higher central electron density. This indicates that the effects of PSF may be not important for the temperature profile but it should be substantial for the determination of the central gas density as well as some other physical properties in the central region, e.g., the cooling-flow rate.

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